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A FUZZY BASED DUTY RATIO APPROACH TO TORQUE RIPPLE MINIMIZATION STRATEGY FOR DIRECT TORQUE CONTROL OF INDUCTION MOTOR

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ABSTRACT

In the conventional DTC, the selected voltage vector is applied for the whole switching period regardless of the magnitude of the torque error. This can result in high torque ripple. A better drive performance can be achieved by varying the duty ratio of the selected voltage vector during each switching period according to the magnitude of the torque error and position of the stator flux. A duty ratio control scheme for an inverter-fed induction machine using DTC method is presented in this paper. The use of the duty ratio control resulted in improved steady state torque response, with less torque ripple than the conventional DTC. Fuzzy logic control was used to implement the duty ratio controller. The effectiveness of the duty ratio method was verified by simulation using MATLAB/SIMULINK.

KEYWORDS: Torque Ripple, Direct Torque Control (DTC), Induction Motor, Fuzzy Logic

INTRODUCTION

The induction motor due to its several advantages has found very wide industrial applications. In recent years much research has been developed in order to find simpler control schemes of induction motors that meet the requirements like low torque ripple, low harmonic distortion and quick response [1]. Direct torque control (DTC) has been recognized in recent decades as a viable control method for high-performance motor drivers since it was invented by Takahashi and Noguchi [2] and Depenbrock [3] (as direct self-control). In addition, it minimizes the use of machine parameters and reduces the complexity of the algorithms involved in FOC and feedback linearization methods. However different from FOC, DTC does not try to reproduce the dynamical behavior of a dc motor but is aimed at the flux and torque-producing capabilities of an induction motor fed by an inverter.

One of the limitations of the conventional DTC are high torque ripple and slow transient response to the step changes in torque during start-up. Several techniques have been developed to improve the torque performance [5-10]. In conventional DTC induction motor drive there are torque and flux ripples because none of method is able to produce the desired changes in both torque and stator flux. However other various techniques are used which can reduce the torque ripples and stator flux. Some of these techniques involve the usage of high switching frequencies or the change of the inverter topology, but it is also possible to use schemes which do not involve any of the mentioned technique, such as the duty ratio control [11].

In this paper a fuzzy controller is used to obtain a duty-ratio that can be used to minimize the torque ripple, simulation results show that the torque ripple is significantly reduced when compared with the classical DTC.

INDUCTION MOTOR MODEL

A dynamic model of the machine subjected to control must be known in order to understand and design vector controlled drives.

Stator Reference

Stator and rotor fluxes can be expressed as follows:

$$\begin{aligned}
\psi_{sD} &= \frac{1}{s}\left(V_{sD} - R_s i_{sD}\right) \\
\psi_{sQ} &= \frac{1}{s}\left(V_{sQ} - R_s i_{sQ}\right) \\
\psi'_{rd} &= \frac{1}{s}\left(V_{rd}' - R_r I_{rd}' - P.w_m \psi_{rq}'\right) = \frac{1}{s}\left(-R_r i_{rd}' - P.w_m \psi_{rq}'\right) \\
\psi_{rq} &= \frac{1}{s}\left(V_{rq}' - R_r i_{rq}' + P.w_m \psi_{rd}'\right) = \frac{1}{s}\left(-R_r i_{rq}' + P.w_m \psi_{rd}'\right)
\end{aligned} \tag{1}$$

Stator and rotor currents can be expressed as follows:

$$\begin{aligned}
i_{sD} &= \psi_{sD} \frac{L_r}{L_x} - \psi_{rd}' \frac{L_m}{L_x} \\
i_{sQ} &= \psi_{sQ} \frac{L_r}{L_x} - \psi_{rq}' \frac{L_m}{L_x} \\
i_{rd} &= \psi'_{rd} \frac{L_s}{L_x} - \psi_{sD} \frac{L_m}{L_x} \\
i_{rq} &= \psi'_{rq} \frac{L_s}{L_x} - \psi_{sQ} \frac{L_m}{L_x} \\
\text{Where } L_x &= L_s L_r - L_m^2
\end{aligned} \tag{2}$$

Rotor Reference

Stator and rotor fluxes can be expressed as follows

$$\begin{aligned}
\psi_{rd} &= \frac{1}{s}\left(V_{rd} - R_r i_{rd}\right) = 0 \\
\psi_{rq} &= \frac{1}{s}\left(V_{rq} - R_r i_{rq}\right) = 0
\end{aligned} \tag{3}$$

$$\begin{aligned}
\psi'_{sd} &= \frac{1}{s}\left(V_{sd}' - R_s I_{sd}' + P.w_m \psi_{sq}'\right) = \frac{1}{s}\left(-R_r i_{rd}' - P.w_m \psi_{rq}'\right) \\
\psi'_{sq} &= \frac{1}{s}\left(V_{sq}' - R_r i_{sq}' - P.w_m \psi_{sd}'\right) = \frac{1}{s}\left(-R_r i_{rq}' + P.w_m \psi_{rd}'\right)
\end{aligned} \tag{4}$$

Stator and rotor currents can be expressed as follows

$$\begin{aligned}
i_{sD} &= \psi'_{sD} \frac{L_r}{L_x} - \psi_{rd}' \frac{L_m}{L_x} \\
i_{sQ} &= \psi'_{sQ} \frac{L_r}{L_x} - \psi_{rq}' \frac{L_m}{L_x} \\
i_{rd} &= \psi_{rd} \frac{L_s}{L_x} - \psi'_{sD} \frac{L_m}{L_x} \\
i_{rq} &= \psi_{rq} \frac{L_s}{L_x} - \psi'_{sQ} \frac{L_m}{L_x} \\
\text{Where } L_x &= L_s L_r - L_m^2
\end{aligned} \tag{5}$$

Motion Equation

The motion equation is as follows

$$t_e - t_L = J\frac{dw_m}{dt} + Dw_m \tag{6}$$

Where, t_e is the electromagnetic torque, t_L is load torque, J is the inertia of the rotor, and finally the D is the

damping constant.

Using the torque expressions, the previous motion equation can be expressed as follows

$$P.c.\left(\psi_{sD}.i_{sQ}-\psi_{sQ}.i_{sD}\right)=t_L+w_m\left(D+Js\right)$$
$$w_r=\frac{P.c.\left(\psi_{sD}.i_{sQ}-\psi_{sQ}.i_{sD}\right)-t_L}{D+Js} \tag{7}$$

Where P is the number of pair of poles and the torque constant take the values either 1 or 2/3 according to the table 1.

Table 1: Torque Constant Values

	Non power invariant		*Power invariant*	
Torque constant	$3/2$		1	
Space phasor constant	*3→2*	*2→3*	*3→2*	*2→3*
	$2/3$	1	$\sqrt{2/3}$	$\sqrt{2/3}$

"3→2" means the change from three axis to either two axis or space phasor notation, and "2→3" either two axis or space phasor notation to three axis.

The SIMULINK model for induction motor is developed by using above equations and simulated successfully. The simulink model is given in figure 1.

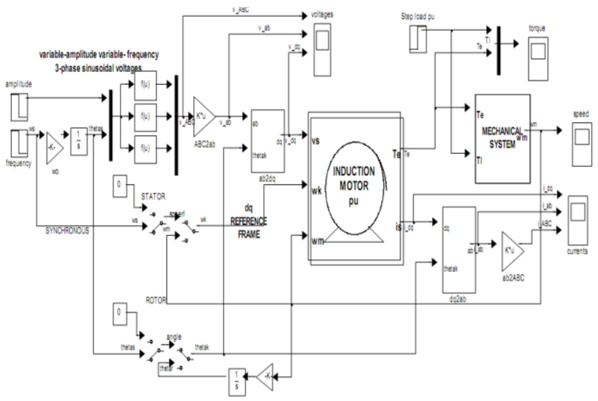

Figure 1: SIMULINK Model for Induction Motor to Obtain Currents and Voltages in Different Frames of References

DIRECT TORQUE CONTROL SCHEMATIC

A possible schematic of Direct Torque Control is shown in figure 2. As it can be seen, there are two different loops corresponding to the magnitudes of the stator flux and torque. The reference values for the flux stator modulus and the torque are compared with the actual values, and the resulting error values are fed into the two level and three-level hysteresis blocks respectively. The outputs of the stator flux error and torque error hysteresis blocks, together with the position of the stator flux are used as inputs of the look up table (see table 2). The inputs to the look up table are given in terms of +1, 0,-1 depend on whether the torque and flux errors within or beyond hysteresis bands and the sector number in which the flux sector presents at that particular instant. In accordance with the figure 2, the stator flux modulus and torque errors tend to be restricted within its respective hysteresis bands.

From the schematic of DTC it is cleared that, for the proper selection of voltage sector from lookup table, the DTC scheme require the flux and torque estimations.

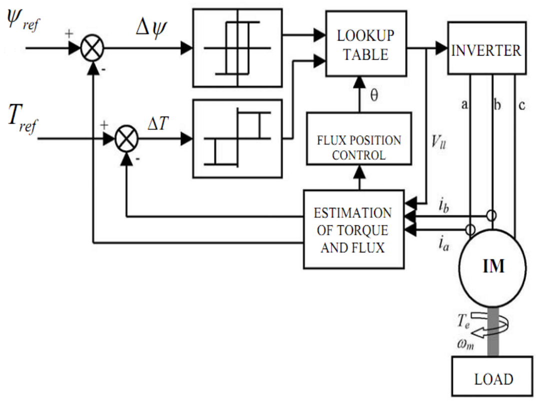

Figure 2: Direct Torque Control Scheme

Table 2: Conventional DTC Look Up Table

Flux Error $d\psi$	Torque Error dT	S1	S2	S3	S4	S5	S6
1	1	V_2	V_3	V_4	V_5	V_6	V1
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_6	Vi	V_2	V_3	V_4	V_5
0	1	V_3	V_4	V_5	V_6	V1	V_2
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_5	V_6	V1	V_2	V_3	V_4

A SIMULINK model shown in figure 3 is developed by using the induction motor model presented in figure 1 and also MATLAB programme is developed for the implementation of conventional DTC. The simulink model for the conventional DTC is developed and is simulated.

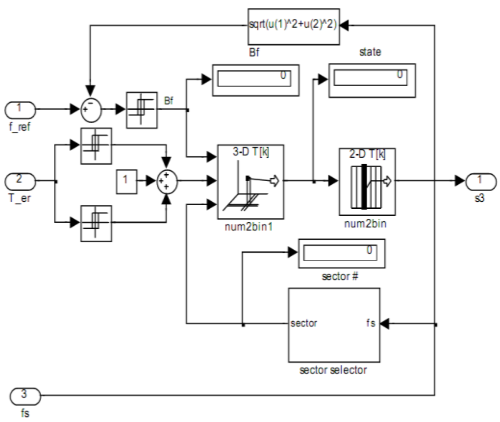

Figure 3: SIMULINK Model for Conventional DTC

FUZZY LOGIC CONTROLLER

Fuzzy logic has rapidly become one of the most successful of today's technology for developing sophisticated control system. Several studies show, both in simulations and experimental results, that Fuzzy Logic control yields superior results with respect to those obtained by conventional control algorithms thus, in industrial electronics the FLC control has become an attractive solution in controlling the electrical motor drives with large parameter variations .

Fuzzy logic expressed operational laws in linguistics terms instead of mathematical equations. Many systems are too complex to model accurately, even with complex mathematical equations; therefore traditional methods become

infeasible in these systems. However fuzzy logics linguistic terms provide a feasible method for defining the operational characteristics of such system [12]. Fuzzy logic controller can be considered as a special class of symbolic controller.

The fuzzy logic controller has three main components

- Fuzzification.
- Fuzzy inference.
- Defuzzification.

Fuzzification

Fuzzy logic's linguistic terms are often expressed in the form of logical implication, such as if-then rules. These rules define a range of values known as fuzzy member ship functions. Fuzzy membership function may be in the form of a triangle, a trapezoidal, a bell or another appropriate form [12].

The triangle membership function is defined in (8).Triangle membership functions limits defined by V_{al1}, V_{al2}, V_{al3}.

$$\mu(u_i)=\begin{cases}\dfrac{u_i-V_{al1}}{V_{al2}-V_{al1}}, V_{al1}\le u_i\le V_{al2}\\ \dfrac{V_{al3}-u_i}{V_{al3}-V_{al2}}, V_{al2}\le u_i\le V_{al2}\\ 0, \quad othetrwise\end{cases} \tag{8}$$

Trapezoid membership function defined in (9). Trapezoid membership functions limits are defined by V_{al1}, V_{al2}, V_{al3} and V_{al4}.

$$\mu_i(u_i)=\begin{cases}\dfrac{u_i-V_{al1}}{V_{al2}-V_{al1}}, V_{al1}\le u_i\le V_{al2}\\ 1, \quad , V_{al2}\le u_i\le V_{al3}\\ \dfrac{V_{al4}-u_i}{V_{al4}-V_{al3}}, V_{al3}\le u_i\le V_{al4}\\ 0 \quad , otherwise\end{cases} \tag{9}$$

The bell membership functions are defined by parameters X_p , w and m as follows:

$$\mu(u_i)=\frac{1}{\left(1+\left(\dfrac{|u_i-X_p|}{w}\right)^{2m}\right)} \tag{10}$$

Where X_p the midpoint and w is the width of bell function $m \ge 1$, and describe the convexity of the bell function.

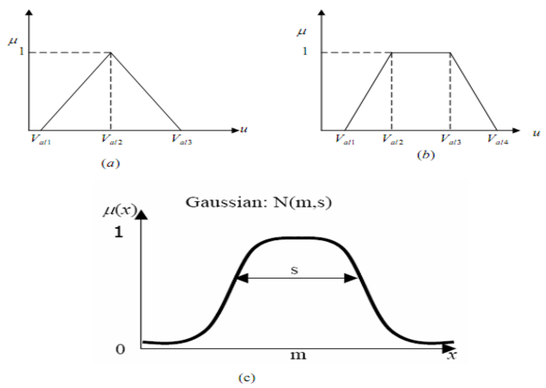

Figure 4: (a) Triangle, (b) Trapezoid, and (c) Gaussian Membership Functions

The inputs of the fuzzy controller are expressed in several linguist levels. As shown in Figure 5 these levels can be described as positive big (PB), positive medium (PM), positive small (PS) negative small (NS), negative medium (NM), negative big (NB) or in other levels. Each level is described by fuzzy set [12].

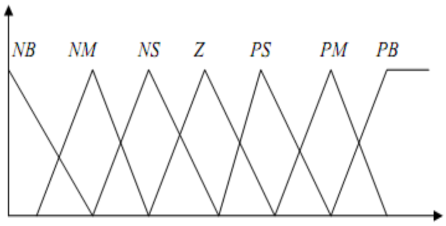

Figure 5: Seven Levels of Fuzzy Membership Function

Fuzzy Inference

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made, or patterns discerned. There are two types of fuzzy inference systems that can be implemented in the Fuzzy Logic Toolbox: Mamdani-type and Sugeno-type. These two types of inference systems vary somewhat in the way outputs are determined.

Defuzzification

The output of the inference mechanism is fuzzy output variables. The fuzzy logic controller must convert its internal fuzzy output variables into crisp values so that the actual system can use these variables [12]. This conversion is called defuzzification.

TORQUE RIPPLE MINIMIZATION IN DTC DRIVES

Figure 6 shows a DTC induction motor drive with a duty ratio fuzzy logic controller.

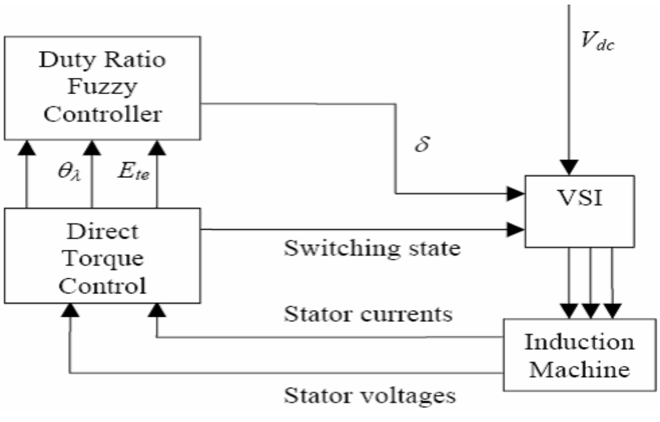

Figure 6: Block Diagram for DTC with Duty Ratio Fuzzy Controller

MATLAB® fuzzy logic toolbox was used in the implementation of the duty ratio fuzzy controller. The Graphic User Interface (GUI) included in the toolbox was used to edit the membership functions for the inputs (the torque error and the flux position), the output (the duty ratio) as shown in Figure 7 and the two sets of fuzzy rules summarized in Table 3. A Mamdani type fuzzy inference engine was used in the simulation.

The membership functions and the fuzzy rules were adjusted using the simulation until an optimal torque ripple reduction was achieved. Figure 8 shows the general view of the fuzzy controller when the stator flux is greater than its reference value.

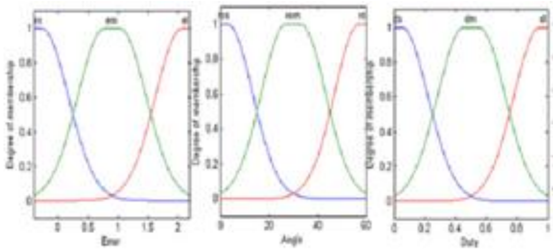

Figure 7: Fuzzy Membership Function

Table 3: Rules for Fuzzy Duty Ratio Controllers

	Torque error	Position of stator flux error		
		Small	medium	large
Stator flux< Ref.Value	small	Medium	Small	Small
	medium	Medium	medium	medium
	large	Large	large	Large
Stator flux> Ref.Value	small	Small	Small	medium
	medium	Medium	medium	Large
	large	Large	large	Large

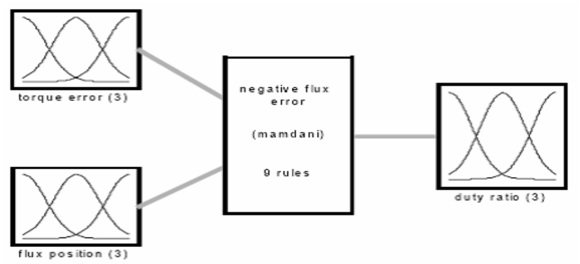

Figure 8: General View of Duty Ratio Fuzzy Controller

SIMULATION RESULTS AND ITS ANALYSIS

A MATLAB programme is developed to study the performance of the conventional DTC and DTC with duty ratio fuzzy controller for 4 pole Induction Motor torque control, and also a SIMULINK model is developed and simulated for the same and verified. Constant torque and flux commands of 1.5 Nm and 0.16Wb were used. The simulation was run at switching frequency of 5 kHz with a 110-V DC bus voltage. The parameters for the induction motor are

Table 4: Parameters of Three Phase Induction Motor

Rs	Rr	Lr	Ls	Lm
1.7Ω	4.3 Ω	0.084H	0.084H	0.082H

The SIMULINK model for DTC with duty ratio fuzzy controller is as shown in figure 9.

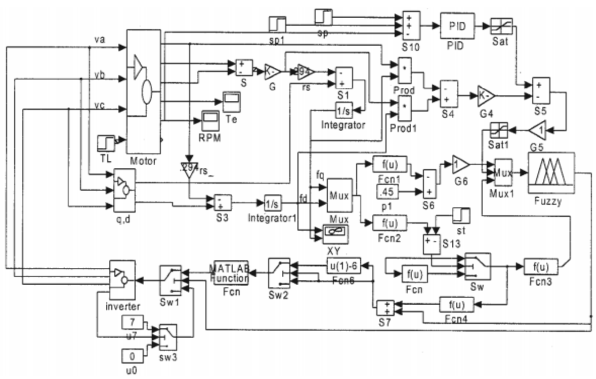

Figure 9: SIMULINK Model for DTC with Duty Ratio Fuzzy Controller

Figure 10 shows the torque response of the motor using conventional DTC and DTC with the duty ratio fuzzy control respectively for a step torque command of 1.5 Nm with the drive output updated at a rate of 5 kHz. The torque ripple is 0.6 Nm (approximately 1.8-1.2 Nm maximum and minimum values respectively) with the conventional DTC while with DTC with the duty ratio fuzzy control the ripple is reduced to 0.32 Nm (approximately 1.62-1.38 Nm maximum and minimum values respectively, neglecting the undershoot in the

Torque Value at the Beginning of Each Voltage Sector

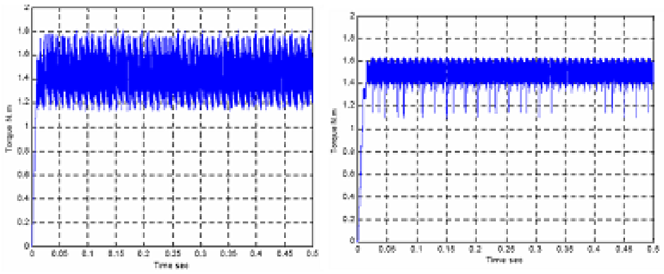

Figure 10: Electric Torque of Induction Motor using (a) Conventional DTC (b) DTC with Duty Ratio FLC

The waveforms of stator current for both conventional DTC and DTC with fuzzy duty ratio controller are shown in figures 11.

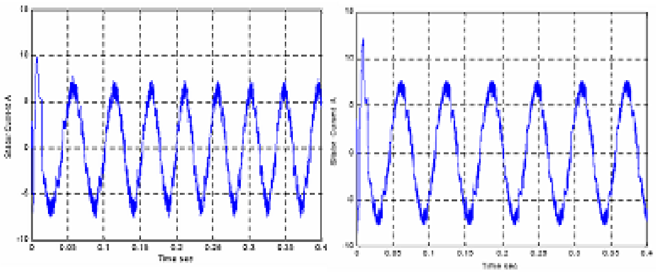

Figure 11: Stator Current Using (a) Conventional DTC (b) DTC with Duty Ratio FLC

Figure 12 shows the stator flux vector locus of the motor using conventional DTC and DTC with the duty ratio fuzzy control, respectively with the controller output updated at a rate of 5 kHz. The duty ratio fuzzy control reduces the stator flux ripple.

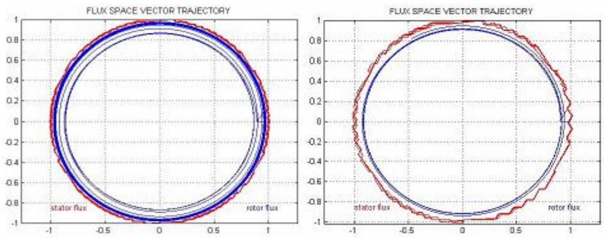

Figure 12: Stator and Rotor Flux Phasor Locus Using (a) Conventional DTC (b) DTC with Duty Ratio FLC

CONCLUSIONS

Duty ratio control can reduce torque ripple in DTC induction motor drives was verified by simulation and experiment. The use of fuzzy logic control gave satisfactory results and reduces the computation burden by avoiding unnecessary complex mathematical modeling of the nonlinear systems. By using duty ratio control a specific motor performance can be achieved at a lower switching frequency compared to the conventional DTC, which in turn increases the efficiency of the drive by reducing losses due to currents and flux harmonics.

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